Archives of Materials Science and Engineering

Volume 64
Issue 1
November 2013
Pages 20-27

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

The effect of polarization plane rotation on binary superlattice transmission

J. Garus [a,*], S. Garus [a], M. Szota [b], M. Nabiałek [a], K. Gruszka [a]
[a] Institute of Physics, Technical University of Częstochowa,
ul. Armii Krajowej 19, 42-200 Częstochowa, Poland
[b] Institute of Materials Engineering, Technical University of Częstochowa,
ul. Armii Krajowej 19, 42-200 Częstochowa, Poland
* Corresponding e-mail address: neit.jb@gmail.com

Received 14.09.2013; published in revised form 01.11.2013

ABSTRACT

Purpose: The purpose of this article is to examine what influence on the transmission has a rotation of the vibration plane, which electric field vector of the electromagnetic wave lies, on the transmission properties of the binary superlattice. In the literature, the most common transmission structure are given for the P or S wave polarization. This article aims to verify the nature of the transmission when the polarization is not strictly defined.

Design/methodology/approach: In the paper the transmission of quasi one-dimensional binary structures is analized depending on the angle of incidence and wavelength of electromagnetic wave and on torsion angle of the plane of the electric field, using the matrix method.

Findings: Changing the angle of rotation of the incident electromagnetic wave electric field vibration plane affects the size of the interband transmission and causes separation of fixed transmission bands locations for specific wavelength and angle of incidence.

Research limitations/implications: Quasi one-dimensional binary superlattices composed of lossless, non dispersive isotropic materials were analyzed. It would be important to investigate influence of loss factor and the two- and three-dimensional periodic and aperiodic structures on the electromagnetic wave transmission. Also important would be to compare results with those obtained from the use of finite increments algorithm in the time domain (FDTD) and the correlation with experimental data.

Practical implications: The test structures may be used as filters of electromagnetic wave propagation. The structure and thickness of the layers has a significant influence on the characteristics of the transmission, which will allow to design the structure in order to met the conditions of specific applications.

Originality/value: In this paper, a method for the analysis of the electromagnetic waves transmission characteristics in the case where the electric field is not polarized in the S, or P directions only.
Keywords: Transmission; Multilayers; Superlattices; Aperiodic; LHM; RHM

Reference to this paper should be given in the following way:

J. Garus, S. Garus, M. Szota, M. Nabiałek, K. Gruszka, The effect of polarization plane rotation on binary superlattice transmission, Archives of Materials Science and Engineering 64/1 (2013) 20-27.

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Filtering capabilities and properties of multilayer systems or advanced composite materials are the subject of intensive research [1-5], and are applicable in photonics, optoelectronics, solid state physics and optics. A unique property of these materials is the fact that electromagnetic waves of certain frequencies does not propagate in their specific systems, there is so-called photonic band gap. These materials do not occur naturally, but are designed and manufactured. Using this materials, photonic crystals [6-12], optical fibre photonic [13], quasi crystals [14-21] and multilayer structures [22-27] were obtained. The class of these structures also includes specific composites called metamaterials, that is, materials with a negative refraction index. The existence of such materials was predicted by Veselago in 1968 [28], in his theoretical work. Experimental confirmation of the Veselago theory took place in 2000 [29], which resulted in increased research of metamaterial structures properties [30-39]. Metamaterials are called left-handed material (LHM), while the conventional dielectric materials are called right-handed material (RHM).

Preparation of multilayer structures is well established [40-44], so the production of selected superlattice structures, with specific thickness of the layers and types of component materials is possible. Simulation of the properties of these structures allows to pre-design them, which implies getting material properties needed for the application. Especially interesting is the use of these structures as filters of electromagnetic radiation in the visible light wavelength range. One way to analyse these properties is to study the transmission level of incident electromagnetic wave. An approach, that can be successfully used to study the transmission properties of these systems is called the matrix method [2]. That method was used in this work, and a brief description is provided below.

Transmission in binary superstructures [2] has already been examined, but the analysis were limited to the TE (S-polarization) or TM (polarization P) polarization only. This article answers the question how the transmission of electromagnetic wave behaves in intermediate states located between the S and P type polarities, for different angles of incidence and for the wavelength of electromagnetic field in range of visible light (300-700 nm).

2. Mathematical introduction

Matrix method has been extensively described in [2, 37]. The following are the basic ready to use formulas and additional correction, using Malus law, which allows for the calculation of transmission for any φ angle of the electric field E intensity vector of vibrational plane rotation. Analysis of the one-layer system elucidates the method for determining the transmission, and after that extend it to a multi-layer model.

Layer structure (Fig. 1) is defined as:

$$n(x)=\begin{cases} n_{in}, & x<0 \\ n_1, & 0\le x\le d \\ n_{out} & x>d \end{cases}, \tag{1}$$

where d is layer thickness; n_{in}, n_{out} are refractive indices of the environment layers from which an electromagnetic wave enters into the structure and comes out. The refractive index is related to the characteristics of the material by the relation:

$$n=\sqrt{\varepsilon_r \mu_r}\ . \tag{2}$$

where ε_r i μ_r are respectively the relative permittivity of the electric and magnetic medium.

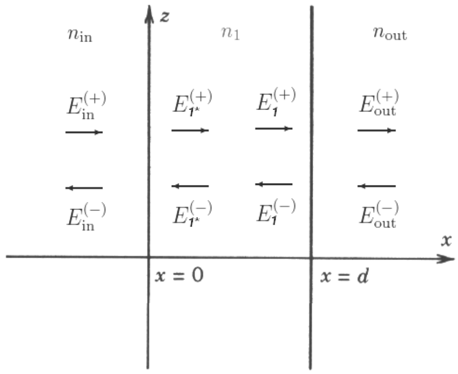

Fig. 1. A thin layer of a dielectric medium [2]

$$E=E(x)e^{i(\omega t-\beta z)}. \tag{3}$$

Equation (3) describes the electric field fulfilling the Maxwell conditions for a homogeneous medium ($\partial n/\partial z = 0$), where ω is the angular frequency, and β is component along z axis of wave vector. $E(x)$ in equation (4) contains components $E^{(+)}(x)$ of the electric field of the electromagnetic wave propagating in the direction of increasing z axis values and $E^{(-)}(x)$ in the opposite direction; k_x is projection of the wave vector on the x axis.

$$E(x)=Ae^{-ik_x x}+Be^{ik_x x}=E^{(+)}(x)+E^{(-)}(x). \tag{4}$$

The electromagnetic wave is polarized as P-type when the magnetic field is parallel to the y axis ($H \parallel y$), while for the S-polarization electric field intensity is parallel to the y axis ($E \parallel y$).

Using of the dynamic matrix D_{in}, D_1 and D_{out} defined as:

$$D_\alpha=\begin{cases}\begin{pmatrix}1 & 1\\ n_\alpha\cos\Theta_\alpha & -n_\alpha\cos\Theta_\alpha\end{pmatrix} & for\quad S\quad polarization\\ \begin{pmatrix}\cos\Theta_\alpha & \cos\Theta_\alpha\\ n_\alpha & -n_\alpha\end{pmatrix} & for\quad P\quad polarization\end{cases}, \tag{5}$$

where $\alpha\in\{in,\ 1,\ out\}$ is the layer number, angles Θ_α are related with Snell's law (Fig. 2), and the components of the wave vector can be defined as:

$$k_{\alpha,x}=\frac{\omega\cdot n_\alpha\cos\Theta_\alpha}{c},\quad \beta_\alpha=\frac{\omega\cdot n_\alpha\sin\Theta_\alpha}{c}, \tag{6}$$

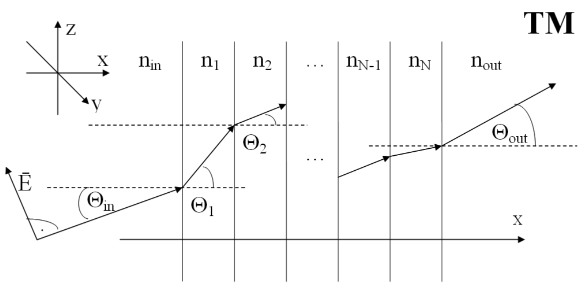

Fig. 2. The distribution of Θ_a angles in multilayer structure for P-type polarization (TM)

A set of equations describing the behavior of the electromagnetic wave propagating in a single layer can be defined as:

$$\begin{cases} \begin{pmatrix} E_{in}^{(+)} \\ E_{in}^{(-)} \end{pmatrix} = D_{in}^{-1} D_1 \begin{pmatrix} E_{1^*}^{(+)} \\ E_{1^*}^{(-)} \end{pmatrix} \equiv D_{in,1} \begin{pmatrix} E_{1^*}^{(+)} \\ E_{1^*}^{(-)} \end{pmatrix} \\ \begin{pmatrix} E_{1^*}^{(+)} \\ E_{1^*}^{(-)} \end{pmatrix} = P_1 \begin{pmatrix} E_1^{(+)} \\ E_1^{(-)} \end{pmatrix} = \begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{-i\phi_1} \end{pmatrix} \begin{pmatrix} E_1^{(+)} \\ E_1^{(-)} \end{pmatrix} \\ \begin{pmatrix} E_1^{(+)} \\ E_1^{(-)} \end{pmatrix} = D_1^{-1} D_{out} \begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)} \end{pmatrix} \equiv D_{1,out} \begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)} \end{pmatrix} \end{cases}. \tag{7}$$

In equation (7) $Ø_1$ is defined as:

$$\phi_\alpha = k_{\alpha,x} d . \tag{8}$$

$D_{in,1}$ and $D_{1,out}$ matrixes combine the amplitude of electric field intensity at the medium borders and will be hereinafter referred to as the transmission matrixes.

For P-type polarization transmission matrix can be defined as:

$$D_{a,b}^{P} = \begin{pmatrix} \frac{1}{2}\left(1 + \frac{n_b^2 k_{a,x}}{n_a^2 k_{b,x}}\right) & \frac{1}{2}\left(1 - \frac{n_b^2 k_{a,x}}{n_a^2 k_{b,x}}\right) \\ \frac{1}{2}\left(1 - \frac{n_b^2 k_{a,x}}{n_a^2 k_{b,x}}\right) & \frac{1}{2}\left(1 + \frac{n_b^2 k_{a,x}}{n_a^2 k_{b,x}}\right) \end{pmatrix}. \tag{9}$$

In contrast, for the S-type polarization transmission matrix takes the form:

$$D_{a,b}^{S} = \begin{pmatrix} \frac{1}{2}\left(1 + \frac{k_{b,x}}{k_{a,x}}\right) & \frac{1}{2}\left(1 - \frac{k_{b,x}}{k_{a,x}}\right) \\ \frac{1}{2}\left(1 - \frac{k_{b,x}}{k_{a,x}}\right) & \frac{1}{2}\left(1 + \frac{k_{b,x}}{k_{a,x}}\right) \end{pmatrix} \tag{10}$$

Equations (9) and (10) can be defined in general form:

$$D_{a,b} = \frac{1}{t_{a,b}} \begin{pmatrix} 1 & r_{a,b} \\ r_{a,b} & 1 \end{pmatrix}. \tag{11}$$

In equation (11) t and r are defined by Fresnel amplitude coefficients. Using those relations:

$$\sigma_{a,b}^{TE} = \sigma_{a,b}^{S} = \frac{k_{b,x}\mu_a}{k_{a,x}\mu_b}, \quad \sigma_{a,b}^{TM} = \sigma_{a,b}^{P} = \frac{k_{b,x}\varepsilon_a}{k_{a,x}\varepsilon_b}. \tag{12}$$

Fresnel transmission coefficients t and reflection r for P and S type polarization are presented in the literature in many equivalent ways [2,37,45], part of them are described by dependencies (13), (14), (15) and (16).

$$t_{a,b}^{P} = \frac{2}{1+\sigma_{a,b}^{P}} = \frac{\frac{2k_{a,x}}{\varepsilon_a}}{\frac{k_{a,x}}{\varepsilon_a} + \frac{k_{b,x}}{\varepsilon_b}} = \frac{\frac{2k_a \cos\Theta_a}{\varepsilon_a}}{\frac{k_a \cos\Theta_a}{\varepsilon_a} + \frac{k_b \cos\Theta_b}{\varepsilon_b}} = \frac{\frac{2n_a \cos\Theta_a}{\varepsilon_a}}{\frac{n_a \cos\Theta_a}{\varepsilon_a} + \frac{n_b \cos\Theta_b}{\varepsilon_b}} = \frac{2\sqrt{\frac{\mu_a}{\varepsilon_a}}\cos\Theta_a}{\sqrt{\frac{\mu_a}{\varepsilon_a}}\cos\Theta_a + \sqrt{\frac{\mu_b}{\varepsilon_b}}\cos\Theta_b} = \frac{2}{1+\sqrt{\frac{\mu_b\varepsilon_a}{\mu_a\varepsilon_b}}\frac{\cos\Theta_b}{\cos\Theta_a}} \tag{13}$$

$$t_{a,b}^{S} = \frac{2}{1+\sigma_{a,b}^{S}} = \frac{\frac{2k_{a,x}}{\mu_a}}{\frac{k_{a,x}}{\mu_a} + \frac{k_{b,x}}{\mu_b}} = \frac{\frac{2k_a \cos\Theta_a}{\mu_a}}{\frac{k_a \cos\Theta_a}{\mu_a} + \frac{k_b \cos\Theta_b}{\mu_b}} = \frac{\frac{2n_a \cos\Theta_a}{\mu_a}}{\frac{n_a \cos\Theta_a}{\mu_a} + \frac{n_b \cos\Theta_b}{\mu_b}} = \frac{2\sqrt{\frac{\varepsilon_a}{\mu_a}}\cos\Theta_a}{\sqrt{\frac{\varepsilon_a}{\mu_a}}\cos\Theta_a + \sqrt{\frac{\varepsilon_b}{\mu_b}}\cos\Theta_b} = \frac{2}{1+\sqrt{\frac{\mu_a\varepsilon_b}{\mu_b\varepsilon_a}}\frac{\cos\Theta_b}{\cos\Theta_a}} \tag{14}$$

$$r_{a,b}^{P} = \frac{1-\sigma_{a,b}^{P}}{1+\sigma_{a,b}^{P}} = \frac{\frac{k_{a,x}}{\varepsilon_a} - \frac{k_{b,x}}{\varepsilon_b}}{\frac{k_{a,x}}{\varepsilon_a} + \frac{k_{b,x}}{\varepsilon_b}} = \frac{\frac{k_a \cos\Theta_a}{\varepsilon_a} - \frac{k_b \cos\Theta_b}{\varepsilon_b}}{\frac{k_a \cos\Theta_a}{\varepsilon_a} + \frac{k_b \cos\Theta_b}{\varepsilon_b}} = \frac{\frac{n_a \cos\Theta_a}{\varepsilon_a} - \frac{n_b \cos\Theta_b}{\varepsilon_b}}{\frac{n_a \cos\Theta_a}{\varepsilon_a} + \frac{n_b \cos\Theta_b}{\varepsilon_b}} = \frac{\sqrt{\frac{\mu_a}{\varepsilon_a}}\cos\Theta_a - \sqrt{\frac{\mu_b}{\varepsilon_b}}\cos\Theta_b}{\sqrt{\frac{\mu_a}{\varepsilon_a}}\cos\Theta_a + \sqrt{\frac{\mu_b}{\varepsilon_b}}\cos\Theta_b} = \frac{1-\sqrt{\frac{\mu_b\varepsilon_a}{\mu_a\varepsilon_b}}\frac{\cos\Theta_b}{\cos\Theta_a}}{1+\sqrt{\frac{\mu_b\varepsilon_a}{\mu_a\varepsilon_b}}\frac{\cos\Theta_b}{\cos\Theta_a}} \tag{15}$$

$$r^S_{a,b}=\frac{1-\sigma^S_{a,b}}{1+\sigma^S_{a,b}}=\frac{\frac{k_{a,x}}{\mu_a}-\frac{k_{b,x}}{\mu_b}}{\frac{k_{a,x}}{\mu_a}+\frac{k_{b,x}}{\mu_b}}=\frac{\frac{k_a\cos\Theta_a}{\mu_a}-\frac{k_b\cos\Theta_b}{\mu_b}}{\frac{k_a\cos\Theta_a}{\mu_a}+\frac{k_b\cos\Theta_b}{\mu_b}}=$$
$$=\frac{\frac{n_a\cos\Theta_a}{\mu_a}-\frac{n_b\cos\Theta_b}{\mu_b}}{\frac{n_a\cos\Theta_a}{\mu_a}+\frac{n_b\cos\Theta_b}{\mu_b}}=\frac{\sqrt{\frac{\varepsilon_a}{\mu_a}}\cos\Theta_a-\sqrt{\frac{\varepsilon_b}{\mu_b}}\cos\Theta_b}{\sqrt{\frac{\varepsilon_a}{\mu_a}}\cos\Theta_a+\sqrt{\frac{\varepsilon_b}{\mu_b}}\cos\Theta_b}= \tag{16}$$
$$=\frac{1-\sqrt{\frac{\mu_a\varepsilon_b}{\mu_b\varepsilon_a}\frac{\cos\Theta_b}{\cos\Theta_a}}}{1+\sqrt{\frac{\mu_a\varepsilon_b}{\mu_b\varepsilon_a}\frac{\cos\Theta_b}{\cos\Theta_a}}}$$

Matrix P_l is a matrix of electromagnetic wave propagation in the medium and is defined as:

$$P_\alpha=\begin{pmatrix} e^{i\phi_\alpha} & 0 \\ 0 & e^{-i\phi_\alpha}\end{pmatrix}. \tag{17}$$

Simplifying the set of equations (7) we get:

$$\begin{pmatrix} E_{in}^{(+)} \\ E_{in}^{(-)}\end{pmatrix}=D_{in}^{-1}D_1P_1D_1^{-1}D_{out}\begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)}\end{pmatrix}=D_{in,1}P_1D_{1,out}\begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)}\end{pmatrix}. \tag{18}$$

Transmission and propagation matrixes from the equation (18) describe the material properties of the multilayer system, which allows to collect them in a matrix Γ, consisting of expressions $M_{i,j}$, and hereinafter referred to as the characteristic matrix.

$$\Gamma=\begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2}\end{pmatrix}=D_{in}^{-1}D_1P_1D_1^{-1}D_{out}=D_{in,1}P_1D_{1,out}. \tag{19}$$

Substituting equation (19) to (18) was obtained:

$$\begin{pmatrix} E_{in}^{(+)} \\ E_{in}^{(-)}\end{pmatrix}=\Gamma\begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)}\end{pmatrix}. \tag{20}$$

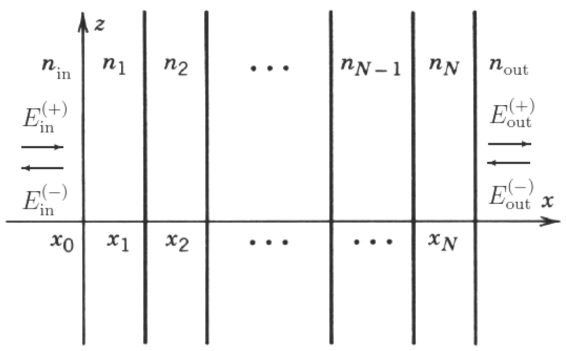

Fig. 3. Dielectric superlattice [2]

Figure 3 shows the multilayer structure defined as:

$$n(x)=\begin{cases} n_{in}, & x<x_0, \\ n_1, & x_0<x<x_1, \\ n_2, & x_1<x<x_2, \\ \vdots & \vdots \\ n_N, & x_{N-1}<x<x_N, \\ n_{out}, & x_N<x, \end{cases} \tag{21}$$

for which the layer thicknesses are defined respectively:

$$\begin{aligned} d_1 &= x_1-x_0 \\ d_2 &= x_2-x_1 \\ &\vdots \\ d_N &= x_N-x_{N-1} \end{aligned}\ . \tag{22}$$

For multilayer systems equation characterizing the behavior of an electromagnetic wave propagating in the structure can be described:

$$\begin{pmatrix} E_{in}^{(+)} \\ E_{in}^{(-)}\end{pmatrix}=\begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2}\end{pmatrix}\begin{pmatrix} E_{out}^{(+)} \\ E_{out}^{(-)}\end{pmatrix}. \tag{23}$$

Characteristic matrix of the dielectric superlattice system after a few simple transformations analogous to the case of a single layer takes the form:

$$\begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2}\end{pmatrix}=D_{in}^{-1}\left[\prod_{i=1}^{N}D_iP_iD_i^{-1}\right]D_{out}. \tag{24}$$

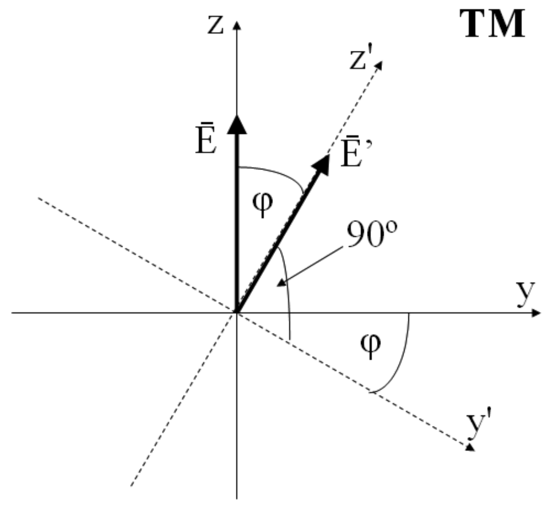

Fig. 4. Rotation of the vibration plane of the electric field intensity by the angle φ

The characteristic matrix can directly determine the T transmission of electromagnetic wave for a multilayer structure

$$T = \frac{n_{out}\cos\Theta_{out}}{n_{in}\cos\Theta_{in}}\left|\frac{1}{M_{1,1}}\right|^2 \tag{25}$$

and reflectance R:

$$R = \left|\frac{M_{2,1}}{M_{1,1}}\right|^2. \tag{26}$$

Note that for the lossless structures between the transmittance and reflectance there is the following relationship:

$$T + R = 1. \tag{27}$$

In order to investigate the effect of the torsion angle φ oscillation plane of the electric field E intensity vector for electromagnetic wave incidenting on the structure, use the Malus law:

$$J(\varphi) = J_0 \cos^2\varphi, \tag{28}$$

where J_0 is the intensity of the incident wave on the polarizer at angle φ, while $J(\varphi)$ is the intensity of the wave at the output of the multilayer structure.

Use of Malus law (28) for determining the transmission (25) leads to the following relationship:

$$T(\varphi) = T^P\cos^2\varphi + T^S\sin^2\varphi, \tag{29}$$

Rotation of the vibration plane of electric field intensity according to the angle φ shows Figure 4.

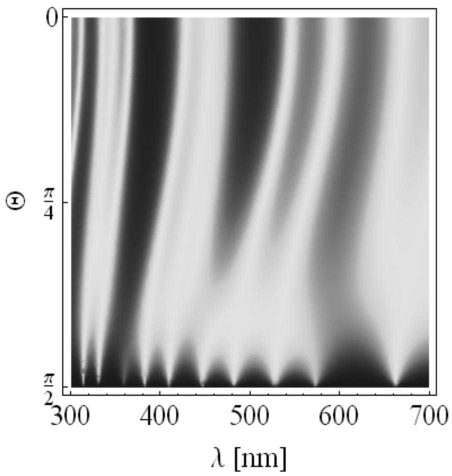

Fig. 5. Transmission map for P-type polarization

3. Research

To analyse the transmission of binary structure the transmission map were used. The horizontal axis indicates wavelength λ [nm] for electromagnetic wave incidenting at an angle Θ relative to the normal of the multilayer structure (Fig. 2). White colour in the graphs indicates the full transmission of the electromagnetic wave of a given wavelength at a given angle, and the black indicates that transmission does not occur. Transmission maps are specified for the P-type polarization ($\varphi = 0°$), S-type ($\varphi = 90°$) or in the case of rotation of the vibration plane of the electric field intensity ($0° < \varphi < 90°$).

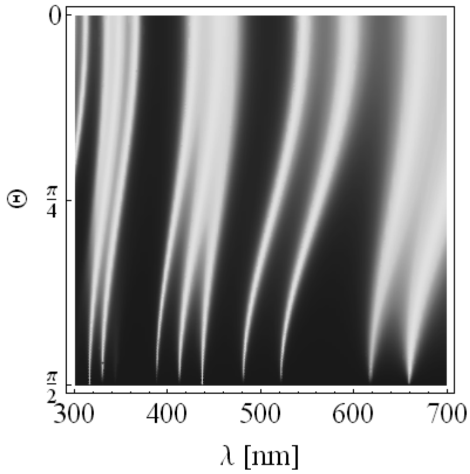

Fig. 6. Transmission map for S-type polarization

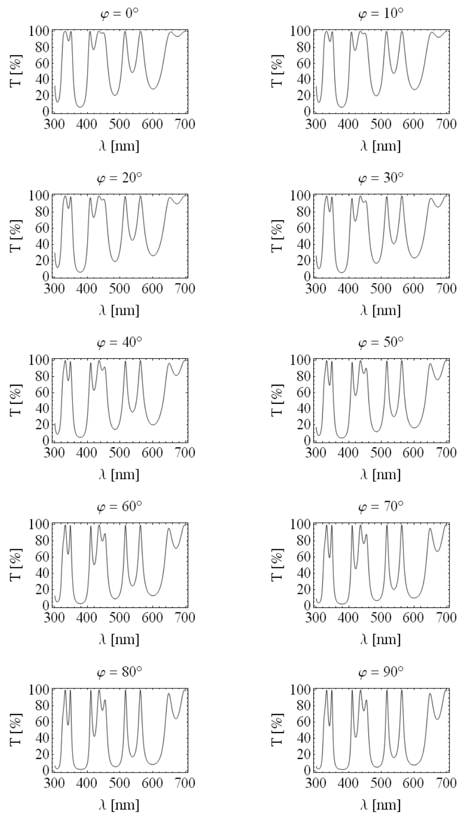

Fig. 7. The transmission of the electromagnetic wave for the angle of incidence $\Theta = 45°$ at difference angles φ

As material A, NaCl was used with refraction index n_A = 1.544 [2]. Material B in studied structure is GaAs, with refraction index n_B = 3.4 [2]. Binary superlattice was also investigated in which the negative refractive index material was used with refraction index set to n_B = - 3.4 to compare the results. Thicknesses are $d_A = d_B$ = 200 nm, and the refractive indices of the surroundings of the multilayer structure take the values $n_{in} = n_{out} = 1$.

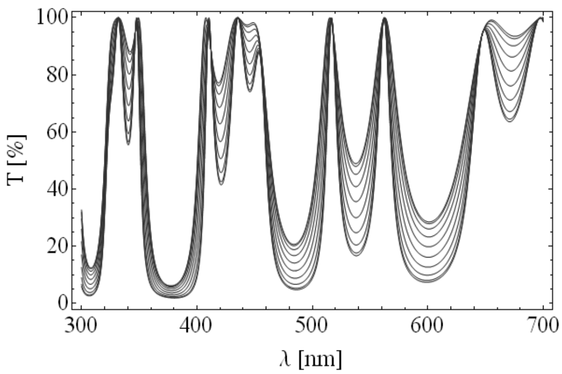

Fig. 8. Imposition of graphs in Figure 7 for the angle of incidence $\Theta = 45°$

The analysed materials are isotropic, lossless and non-dispersive.

Binary superlattice consists of repetitions of AB cluster, where the notation AB means that the first material is material A with refractive index n_A and thickness d_A, and on it material B was sprayed with a refractive index respectively, n_B and layer thickness d_B. Network generation k for binary superlattice is the number of repetitions for cluster AB, which means, that for $k = 3$ the structure ABABAB is created, for which the transmission maps were obtained (Figures 5-7).

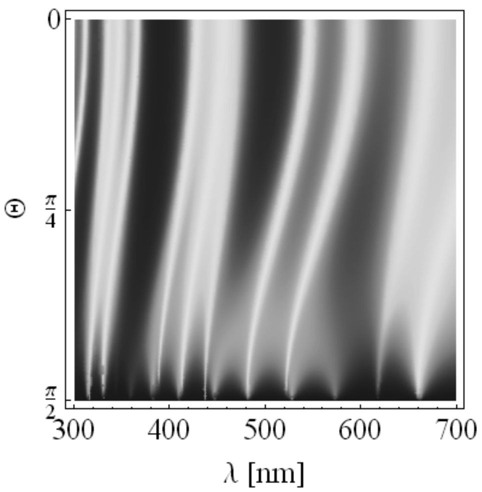

Fig. 9. Map of the transmission for the rotation angle of the vibration plane vector of electric field intensity equal to $\varphi = 45°$

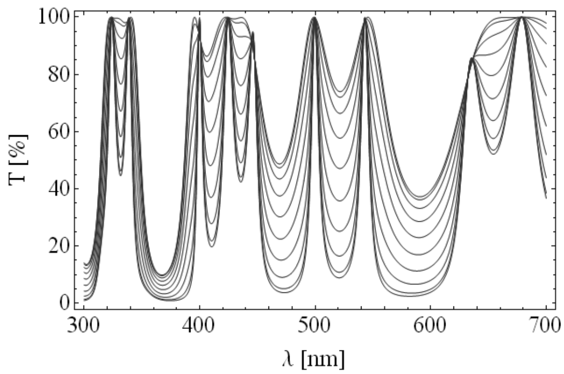

Fig. 10. Imposition of transmission graphs for different angles φ with $\Theta = 30°$

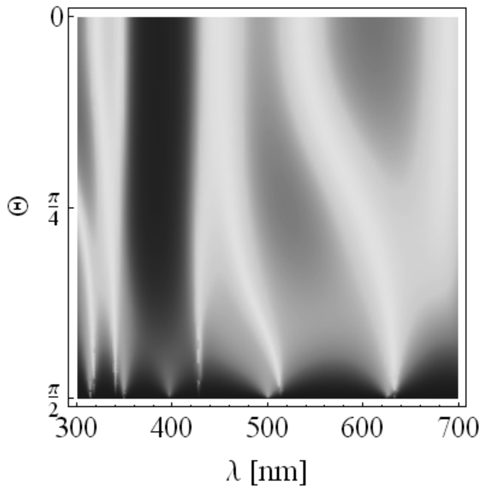

Fig. 11. Transmission map for plane torsion of electric field vibrations of electromagnetic wave with angle $\varphi = 45°$, for n_B = - 3.4

It can be seen that the superlattice structure results in characteristic transmission bandwidth. The band structure strongly depends on the type of polarization.

Figure 7 shows the transmission depending on the length of the electromagnetic wave. Wave incidented at a constant angle $\Theta = 45°$ to a multilayer structure, only the angle φ were changing. On Figure 8 plots from Figure 7 were imposed in order to find repeated regularity. It was also noted the occurrence of location fixed transmission bands for specific wavelength. The influence on size of the transmission of interband space affects change of electric field's torsion angle φ of oscillation.

Figure 9 shows a map of the transmission for the rotation angle of the vibration plane vector of electric field intensity equal to $\varphi = 45°$. It should be noted isolation of characteristic bands, constant for both polarizations.

Comparison of Figs. 8-10 shows that for every angle of incidence of the electromagnetic wave Θ transmission peaks with a fixed value are formed, and changing the angle φ in a nonlinear way affect the interband spaces.

Figures 11 and 12 shows the structure of a transmission for a vibration angle rotation of the electromagnetic wave's electric field plane equal to φ = 45°, in case, when material B has a negative refractive index n_B = - 3.4. For Figure 13 torsion angle is φ = 30°.

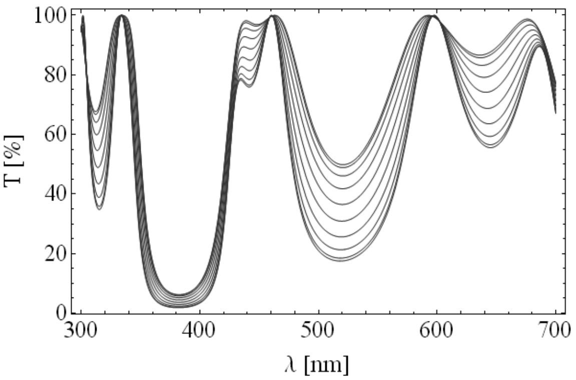

Fig. 12. Imposition of transmission graphs for different angles φ with Θ = 45°, for n_B = - 3.4

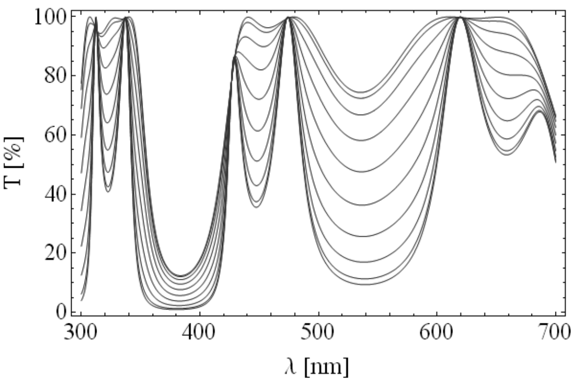

Fig. 13. Imposition of transmission graphs for different angles φ with Θ = 30°, for n_B = - 3.4

4. Conclusions

The obtained results indicate:

- the transmission has a band structure, but the bandwidth is wide and bands are not separated from each other,
- polarization of the incident wave significantly affects the transmission of the structure ABA,
- change the material B refractive index from RHM to LHM significantly alters the transmission,
- change the angle of torsion φ of the electric field's oscillation plane affects the size of space of interband transmission,
- the presence of fixed transmission bands for specific wavelength and angle of incidence when changing the torsion angle φ.

Understanding the properties of multilayer structures affect the ability of filter design of electromagnetic waves with characteristics suited to application data. Especially important is to learn the properties of metamaterials and their impact on the transmission of system because their characteristics are promising and also only partially understood.

It appears advisable to investigate the influence of the angle φ on the transmission properties of aperiodic structures, as well as two and three dimensional structures and the correlation of results with experimental data. For further consideration also should be taken impact of angle φ of lossy materials with a specific dispersion.

References

[1] M. Born, E. Wolf, Principles of Optics, Pergamon Press, London, 1968.
[2] P. Yeh, Optical Waves in Layered Media, Publishing house John Wiley and Sons, New York, 1988.
[3] L. M. Briechowski, Wołny w słoistych sriedach, Publishing house Nauka, Moskwa, 1973.
[4] A. Yariv, P. Yeh, Optical Waves in Crystals. Propagation and Control of Laser Radiation, Publishing house John Wiley and Sons, New York, 1984.
[5] A. Rostami, S. Matloub, Exactly solvable inhomogeneous Fibonacci-class quasi-periodic structures (optical filtering), Optics Communications 247 (2005) 247-256.
[6] S. John, Strong localization of photons in certain disordered dielectric superlattices, Physical Review Letters 58 (1987) 2486-2489.
[7] E.Yablonovitch, Inhibited Spontaneous Emission in Solid-State Physics and Electronics, Physical Review Letters 58 (1987) 2059-2062.
[8] E.Yablonovitch, Photonic crystals, light semiconductors, The World of Science 126 /2 (2002) 46-53 (in Polish).
[9] J.D. Joannopoulos, R. D. Meade, J. N. Winn, Photonic Crystals. Molding the Flow of Light, Princeton University Press, Singapore, 1995.
[10] S.G. Johnson, J. D. Joannopoulos, Photonic Crystals. The Road from Theory to Practice, Kluwer Academic Publishers, Boston, 2002.
[11] D.J. Lockwood, L. Pavesi (Eds.), Silicon Photonics, Topics in Applied Physics 94, Springer-Verlag Berlin Heidelberg, 2004.
[12] K. Sakoda, Optical Properties of Photonic Crystals, Publishing house Springer-Verlag Berlin, 2001.
[13] A. Bjarklev, J. Broeng, A. S. Bjarklev, Photonic Crystal Fibers, Kluwer Academic Publishers, Boston, 2003.
[14] D.S. Shechmtan, I. Blench, D. Gratias, J. W. Cahn, Metallic phase with long-ranged orientational order and no translational symmetry, Physical Review Letters 53 (1984) 1951-1953.
[15] D. Levine, P.J. Steinhardt, Quasicrystals: A new class of ordered structures, Physical Review Letters 53 (1984) 2477-2480.
[16] D. Levine, P.J. Steinhardt, Quasicrystals. I. Definition and structure, Physical Review B 34 (1986) 596-616.
[17] P.J. Steinhardt, S. Ostlund, The Physics of Quasicrystals,World Scientific, Singapore, 1987.
[18] P. Guyot, P. Krammer, M. de Boissieu, Quasicrystals, Reports on Progress in Physics 54 (1991) 1373-1425.

[19] D.P. Di Vincenzo, P.J. Steinhardt (Eds.), Quasicrystals: The State of the Art, World Scientific, Singapore, 1991.
[20] S.J. Poon, Electronic properties of quasicrystals, An experimental review, Advances in Physics 41 (1992) 303.
[21] Ch. Hu, R. Wang, D.-H. Ding, Symmetry groups, physical property tensors, elasticity and dislocations in quasicrystals, Reports on Progress in Physics 63 (2002) 1-39.
[22] L. Esaki, R. Tsu, Superlattice and negative differential conductivity in semiconductors, IBM Journal of Research and Development 14 (1970) 61-65.
[23] A. Wacker, Semiconductor superlattices: a model system for nonlinear transport, Physics Reports 357 (2002) 1-111.
[24] M. Gluck, A.R. Kolovsky, H.J. Korsch, Wannier-Stark resonances in optical and semiconductor superlattices, Physics Reports 366 (2002) 103-182.
[25] E.L. Albuquerque, M.G. Cottam, Theory of elementary excitations in quasicrystals structures, Physics Reports 376 (2003) 225-337.
[26] E. Abe, Y. Yan, S.J. Pennycook, Quasicrystals as cluster aggregates, Nature Materials 3 (2004) 759-767.
[27] X. Zhou, Ch. Hu, P. Gong, Sh. Qiu, Nonlinear elastic properties of decagonal quasicrystals, Physics Review B 70 (2004) 94202-94206.
[28] V. G. Veselago, Elektrodinamika veshchestv s odnovremeno otricatelnymi znacheniami ε i μ, Uspekhi Fizicheskikh Nauk 92 (1968) 517-529.
[29] D.R. Smith, W. J. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, Composite Medium with Negative Permeability and Permittivity, Physical Review Letters 84 (2000) 4184-4187.
[30] E. Cubukcu, K. Aydin, E. Ozbay S. Foteinopoulou, C.M. Soukoulis, Subwavelength Resolution in a Two-Dimensional Photonic-Crystal-Based Superlens, Physical Review Letters 91 (2003) 207401.
[31] E. Cubukcu, K. Aydin, E. Ozbay, S. Foteinopoulou, C.M. Soukoulis, Electromagnetic waves: Negative refraction by photonic crystals, Nature 423 (2003) 604-605.
[32] K. Yu. Bliokh, Yu. P. Bliokh, What are the left-handed media and what is interesting about them, Uspekhi Fizicheskikh Nauk 174 (2004) 439.
[33] P. Markos, C.M. Soukoulis, Left-handed Materials, avaliable in EBP arXiv:condmat/0212136, (2002).
[34] A.L. Pokrovsky, A. L. Efros, Sign of refractive index and group velocity in left-handed media, Solid State Communication 124 (2002) 283-287.
[35] C.M. Krowne, Y. Zhang, (Eds), Physics of Negative Refraction and Negative Index Materials, Publishing house Springer-Verlag Berlin Heidelberg, 2007.
[36] S.A. Ramakrishna, T.M. Grzegorczyk, Physics and Applications of Negative Refractive Index Materials, SPIE Press and CRC Press, 2009.
[37] A. Klauzer-Kruszyna, Propagation of polarized light in selected aperiodic superstructures, PhD Thesis, Wrocław, 2005 (in Polish).
[38] S. Garus, M. Duś-Sitek, E. Zyzik, Effect of iron dopant on superlattice FexNi (1-x) / Cu transmission properties, New Technologies and Achievements in Metallurgy and Materials Engineering, Proceedings of the 12th International Scientific Conference, Częstochowa, 2011 (in Polish).
[39] S. Garus, J. Garus, K. Gruszka, Emulation of Electromagnetic Wave Propagation in Superlattices Using FDTD Algorithm. New Technologies and Achievements in Metallurgy and Materials Engineering, Publishing house University of Technologies WIPMiFS Częstochowa (2012) 768-771 (in Polish).
[40] L. Jacak, P. Hawrylak, A.Wójs, Quantum Dots, Publishing house Springer-Verlag Berlin Heidelberg, New York, 1998.
[41] H.S. Nalwa (Ed.), Nanostructured Materials and Nanotechnology, Academic Press, New York, 2002.
[42] M. Kohler, W. Fritzsche, Nanotechnology: an introduction to nanostructuring techniques, Wiley-VCH Verlag, Weinheim, 2004.
[43] Z.L. Wang, Y. Liu, Z. Zhang (Eds.) Handbook of nanophase and nanostructured materials 1 Synthesis, Kluwer Academic/Plenum Publishers, New York, 2003.
[44] M. Jurczyk, J. Jakubowicz, Ceramic Nanomaterials, Publishing house Poznań University of Technology, Poznań, 2004.
[45] W. Steurer, S. Deloudi, Crystallography of Quasicrystals, Springer Series in Materials Science, 126, Publishing house Springer Verlag, Berlin, 2009.